11. IMPROVEMENTS IN THERMODYNAMICS OF SCRAMJET MHD CONCEPT

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Abstract. New concepts of energy recycling in hypersonic propulsion system are now being considered. In particular, the technologies, proposed in the AJAX hypersonic vehicle concept, include MHD conversion of kinetic energy of the inlet flow and application of this energy for plasma acceleration at the outlet of the engine flow train. Unless the problem of technical feasibility of plasma generation is considered, the fundamental problem relates to minimization of dissipative losses in MHD devices integrated into the propulsion system, as well as in the conventional components, i.e. the inlet diffuser and combustor.

In the present paper a comparative thermodynamic analysis of various configurations of hypersonic propulsion system with MHD bypassing of flow energy is accomplished. The conventional scheme of airbreathing propulsor, the AJAX type MHD propulsion system and newly proposed engines with MHD devices are analysed. The new modified propulsion scheme differ from the AJAX concept by bypassing both kinetic and thermal energy from combustor to the plasma accelerator.

At typical for hypersonic propulsion values of temperature and pressure the application of the ideal gas approximation leads to an error of the parameter magnitude. So, the real thermodynamic properties were taken into account. The numerical codes of various thermodynamic processes were developed. This allowed to compose the cycles of interest for different types of engine. The special attention was paid to simulation of multishock diffuser with assigned shock number and intensities. For this a special iterative procedure was introduced.

The comparison of different systems was made at the preset limitation on the maximum value of static temperature in the engine. This value was chosen as 3000K. Additionally, in the combustor the flow velocity was limited (when that was possible) at 1700m/s.

The thermodynamic cycles of various hypersonic propulsion systems were computed. The results reveal that of the chosen limitations the only temperature limitation can be satisfied in the conventional scramjet, whereas the velocity in the combustor substantially exceeds the limit. The implementation of MHD bypassing of the AJAX type allows the flow parameters to be within the limitations, but the loss of thrust occurs due to enhanced entropy increase. The system modification restore the thrust to the value quite near to that of conventional scramjet.

Introduction

The velocity of aircraft equipped by ramjet engine should rise with increase of flight altitude in order to compensate a reduction of environmental air density. At the flight altitude of about 30km the rated flight Mach number providing an air flow rate needed to maintain a specified value of the thrust equals to 7-8. In spite of a high quality of modern supersonic diffusers a deceleration of such flow down to subsonic velocity occurs with high shock-wave losses sharply decreasing the propulsion system efficiency. Furthermore, deep deceleration of the hypersonic flow results in substantial increase of static temperature which may achieve very high values (~ 3500K and higher). At these temperatures a radiation component will dominate in a radiative-convective heat transfer, and the conditions of thermal resistance of the propulsion system design dictate a limitation on static temperature. This limitation in the flow train is partly met by increasing of velocity. This can be allowed till the velocity in the combustor reaches value at which the stable combustion breaks off. Thus, a new limitation on maximum flow velocity arises.

These problems may be lessened by application of supersonic combustor operating at high velocity of motion of reacting components. An overview of the main aspects and problems of physics of the supersonic combustion for application to conventional design of scramjet has been given in the classical work [1]. A great attention has been given to this research direction. Nevertheless, to date only one flight experiment has been performed with Mach number M=5 [2]. According to estimations at M > 8 kinetic energy of freestream flow is so high that engineering constraints on static temperature after heat release in the combustor may be met only at the very high flow velocity whereby it is difficult to arrange an efficient combustion process. In so doing, the development of supersonic combustor for scramjet of conventional design will require more considerable efforts and time and is being problematic yet.
In parallel a search of new approaches to the scramjet operation organization is continuing to provide an acceptable efficiency of the propulsion system under the engineering constraints. One of them is the AJAX concept based on application of MHD technology to bypass kinetic energy from a supersonic diffuser into a nozzle [3-6]. According to this concept the scramjet design incorporates MHD generator located between the diffusor and the combustor and MHD accelerator desposed between the combustor and the nozzle. An MHD generator is used for conversion of part of the flow kinetic energy into electrical energy that is transferred to an MHD accelerator for additional acceleration of combustion products. The concept authors supposed that combined (geometric and magnetohydrodynamic) method of the flow deceleration in front of the combustor will allow to reduce the flow velocity to acceptable value at the less dissipation losses and with satisfaction of corresponding constraints. The estimation of prospects of the concept depends on answers to two questions. The first question concerns with the thermodynamic analysis of the scheme efficiency in comparison with conventional design of the scramjet. The second question refers to feasibility of the concept proposed, i.e. a possibility of arrangement of efficient operation of MHD devices at specific parameters of the working fluid in the scramjet duct and under existing mass and dimension constraints. It is evident that consideration of the second question has a sense if the first one will have the positive respond.

The thermodynamic analysis of the scramjet scheme within the framework of the AJAX concept was the initial goal of the present work. However, in the process of performed analysis, having revealed imperfections of the concept, a proposal on the concept modification was arised to bypass the energy (both kinetic and thermal) directly from combustor. It means a combination of combustor and MHD generator, since an MHD energy conversion inside of the combustor and MHD accelerator desposed on the combustor and MHD generator is preferable from considerations of thermodynamic efficiency. MHD accelerator may be combined with the nozzle as well occupying some its segment. The thermodynamic advantages of this scheme are found out by comparative analysis of the cycles described in the present work. It should be mentioned that description of the scramjet cycles in terms of efficient values of non-ideality of processes of compression and expansion was given in [7], and general approaches to thermodynamical analysis of AJAX design were outlined in the recent work [8] where perfect gas approximation was used and a constraint on stagnation temperature was applied to the propulsion system flow train.

**Cycle configuration and implied assumptions**

Let us consider the thermodynamic cycles of three scramjet schemes mentioned above (their simplified block-diagram is given in Figs.1-3). For the initial point of the cycles the parameters of air flow corresponding to flight altitude of about 30km and Mach number $M_1=8$ are equal to the following values: pressure $p_1=0.012$atm, temperature $T_1=230.3K$, velocity $u_1=2436m/s$, enthalpy $h_1=55kcal/kg$, entropy $s_1=1.97kcal/kg K$. The fuel combustion heat $Q_c$ is taken as 826kcal/kg, that approximately corresponds to hydrogen combustion in air. The range of variation of static parameters in the scramjet flow train under intensive flow deceleration is very wide, and application of perfect gas model leads to an error in determination of the cycle parameters. In this connection the analysis is performed for real air properties which were defined by diagrams of its thermodynamical functions [9]. The cycles are constructed in coordinates of static enthalpy $h$ and entropy $s$.

It was supposed that the compression process in the supersonic diffuser is adiabatic and goes along a curve approximating a system of three oblique shocks followed by a normal shock wave of equal stagnation pressure ratio. It was assumed that the working fluid expansion in a nozzle is isentropic, and the processes in MHD devices are isothermal. The other assumptions are common hypotheses used for the thermodynamical analysis. An aircraft velocity, freestream parameters, fuel combustion heat and integral efficiency factor of MHD devices are assumed as fixed parameters for all calculations. A comparison of different schemes was performed in terms of specific thrust of propulsion system taking into account engineering constraints on maximum allowable static temperature and velocity in combustor.

To describe the technique of the cycle construction and particular assumptions used for the cycle models development let us consider each of the scheme consequently.

**Conventional scramjet design** (Fig.1) falls into family of Brayton cycles and consists of 2 adiabatic processes: compression in the supersonic diffuser (points 1-2 in Fig.1) and expansion in the nozzle (points 3-4), and two isobaric processes: heating in combustor (points 2-3) and heat rejection into atmosphere (points 4-1).

The flow kinetic energy $W_2=\frac{1}{2}u_2^2 / 2$ at the diffuser outlet (completion of compression process corresponds to point 2) was defined by a factor $k_{sd}=W_2 / W_1$, that was varied from 0.01 to 0.75. It was assumed that the compression process in the diffuser up to velocity $u_2$ occurs along the curve
approximating in $h$-$s$ coordinates a system of three oblique shocks and followed normal shock wave. Relative losses of stagnation pressure for every of the shocks were predetermined as roughly equal: $p_{0b}/p_{0a+k-1} = 2$, that for fixed number of shocks provides integral shock-wave losses in the supersonic diffuser closed to minimum value (corrections of Oswatitsch’s results [10] made in [11,12] are not critical for goals of the present study).

![Fig.1. Simplified block-diagram of the conventional scramjet scheme.](image)

Application of graphic diagrams of air thermodynamic functions notably complicates the task of description of the shock waves system. To solve the problem an iterative algorithm has been developed based on expressions for pressure and enthalphy after the shock wave:

$$
\begin{align*}
    p_a &= p_{i+1}^a p_{0b}^{0a} (1-u_{na}/u_{nb})^2, \\
    h_a &= h_b + 0.5 u_{nb}^2 (1-u_{na}/u_{nb})^2.
\end{align*}
$$

The expressions follow from conservation equations for the shock wave written in terms of velocity component normal to the shock front, subscripts “b” and “a” designate conditions before and after the shock wave, correspondingly. Value $u_{nb}$ is defined by an angle $\varphi$ between velocity vector and the shock wave front: $u_{nb} = u_0 \sin \varphi$. The value of angle $\varphi$ is assigned to provide given ratio $p_{0b}/p_{0a+k-1}$.

The iterative process is constructed in the following way. By the value $u_{na}$ obtained in the previous iteration ($u_{na}^0 = 0$ may be used as an initial approximation for $u_{na}$), the new values of $p_{i+1}^a$ and $h_{i+1}^a$ are calculated, then temperature and molar mass after the shock wave are determined from diagrams:

$$
T_{i+1}^a = T(h_{i+1}^a, p_{i+1}^a), \quad \mu_{i+1}^a = \mu(h_{i+1}^a, p_{i+1}^a).
$$

The new density value is determined from the thermal equation of state:

$$
p_{i+1}^a = p_{i+1}^a h_{i+1}^a / (R_m T_{i+1}^a),
$$

where $R_m$ is absolute gas constant. Finally, from equation of flow mass conservation the new value of velocity $u_{na}$ is calculated:

$$
u_{na}^i = u_{nb}^i \sqrt{p_{0a}/p_{i+1}^a}.
$$

The process is finished when $|1 - u_{na}^{i+1} / u_{na}^i| \leq \varepsilon = 10^{-3}$. For its complete convergence, as a rule it is enough to perform 5-6 iterations. If it is needed the value of $\varphi$ is corrected and the process is repeated to the extent of assigned ratio $p_{0b}/p_{0a+k-1}$. With this algorithm the flow parameters after each shock wave were obtained and deceleration curve was plotted with the outlet velocity $u_2 = 243$ m/s. The compression process completion in the diffuser at the specified value of $k_{SD}$ (point 2 in $h$-$s$ diagram) is defined by intersection of deceleration curve and isenthalpy line $h = h_2 = h_3 = u_2^2/2 = \text{const}$.

When the combustion process in combustor was analyzed, the mass flow rate increase due to fuel injection was as usually neglected and an absence of pulse losses due to wall friction and heat losses was assumed. This assumption means that due to isobaric condition the flow velocity at this part of the cycle is constant, and variations of static and total enthalpy are equidistant. Thus, the completion of this process (point 3) corresponds to intersection of isobaric curve $p = p_2$ and isenthalpy line $h = h_3 = h_4 = Q_C$.

Dissipative losses in acceleration of combustion products in the nozzle do not play a notable role in the comparative analysis. In the case, when nozzle velocity coefficient $u_{4\text{ideal}}/u_{4\text{ideal}}$ is constant, we can consider the expansion process in the nozzle as isentropic and, accordingly, it may be presented in $h$-$s$ diagram by vertical line segment from point 3 to intersection with isobar curve $p = p_4$ (point 4). The cycle is closed by this isobaric curve.

For the comparative analysis the following values of $k_{SD}$ were chosen: 0.01, 0.25, 0.5, 0.75. Effect of shock-wave losses in the diffuser on efficiency of conventional scramjet scheme at different $k_{SD}$ was discovered by comparison of the cycles constructed with application of the technique described above (case B) and with an assumption that the compression process in diffuser is isentropic (ideal) (case A).

**AJAX concept** (Fig.2), as noted above, differs from the conventional scramjet design in particular by a presence of additional devices in the propulsion system: MHD generator (MHDG) and MHD accelerator (MHDA).

MHDG is installed between supersonic diffuser and combustor, and MHDA is located between combustor and nozzle. Accordingly, the cycles constructed for this design include additional processes: 2-2m – MHD energy generation and 3-3m – MHD flow acceleration.
The modification of AJAX concept (RAM-MHD scheme) proposed in the present paper is an attempt to meet the engineering limitations on velocity and static temperature in combustor with retention of high efficiency of the propulsion system. The basic idea of the modification is to bypass both kinetic and thermal energy of flow from the combustor to the nozzle, for which purpose MHD devices are combined (totally or partially) with combustor, nozzle or other components of the engine. In the present paper a variant of RAM-MHD scheme is considered (Fig.3) where the combustor is partitioned into 3 sections: the first one is isobaric and two others are isothermal.

In the first section combustion proceeds at the constant pressure and velocity. When the static temperature \( T_{lim} \) limiting for the combustor is achieved, the flow enters the second section of combustor, where the the duct geometry provides isothermal combustion process at \( T = T_{lim} \). In this case the flow velocity increases, and in the point corresponding to velocity \( u = u_{lim} \) the third section of combustor starts where combustion proceeds concurrently with MHD power generation. It is assumed, that this combined process in the third section is arranged in such a way that simultaneously constant temperature and velocity are maintained: \( T = T_{lim} \), \( u = u_{lim} \). This is possible because of the combustion heat release in this section.

Isobaric combustion process in the first combustor section is completed in the point of intersection of curves \( p = p_2 \) and \( T = T_{lim} \) (point 3p). All assumptions taken above for description of combustor of conventional scramjet design are valid for this process, so the fraction of combustion heat \( Q_{cp} \) released in the first section, is defined as a difference of static enthalpies in the beginning and the end of the process: \( Q_{cp} = h_{2m} - h_2 \).

Condition \( T = T_{lim} \) is fulfilled in the second section of the combustor due to flow acceleration from the...
Velocity \( u_3 = u_2 \) up to the velocity \( u_3 = u_{lim} \). The combustion process in this section continues up to point 3t. At this point the stagnation enthalpy is equal to \( h_{3t} = h_{3} + 0.5 u_{lim}^2 \). The combustion process was performed in terms of the AJAX scheme. Since in isothermal process \( Q_{ct} \) is equal to \( T_{lim}(s_3-s_3p) \) and an equation

\[
h_{3t} + 0.5 u_{lim}^2 = h_{3p} + T_{lim}(s_3-s_3p)
\]
defines implicitly value \( s_3p \). This equation was solved using graphs in the \( h-s \) diagram. Through the point with coordinates \( (s_3p, h_{3p}) \) corresponding to stagnation parameters of the beginning of the process under consideration, the straight line \( h-h_{3p}=T_{lim}(s-s_3p) \) is drawn, after that such a value of entropy \( s_3p \) was defined, for which a distance between the drawn straight line and isothermal curve \( T = T_{lim} \) is equal to kinetic energy at the end of this section \( W_3 = u_{lim}^2/2 \).

In so doing, heat \( Q_{cm} \) released in the third section of combustor is determined as \( Q_{cm} = Q_{c} - Q_{ct} \). An entropy increment in this section is equal to \( s_{3m-s_3p} = (Q_{cm} + Q_{eg})/T_{lim} \), where \( Q_{eg} \) is Joule heat released in MHDA. As in the case of the AJAX scheme, Joule heat release \( Q_{eg} \) is related to electrical power \( N_{eg} \) by relation \( Q_{eg} = (1-n_{eg}) N_{eg} \). Value of \( N_{eg} \) was defined as \( N_{eg} = Q_{cm} - (h_{3m}-h_{3p}) \). Electric efficiency factor is specified as \( n_{eg} = 0.8 \).

Construction of cycles of RAM-MHD scheme (case D) is completed by description of processes of acceleration of combustion products in MHDA that was performed in the same manner as for the AJAX scheme.

Comparison of different schemes of propulsion system was performed in terms of values of specific thrust that is difference of velocities \( u_4 - u_1 \) with regard to specified constraints on maximum allowable values of static temperature in the flow train \( T_{lim} = 3000 \)K and velocity in the combustor \( u_{lim} = 1700 \)m/s.

**Calculation results and their analysis**

Plots of four cycles constructed for conventional scramjet design with assumption of isentropic process of flow deceleration in diffusor (case A) are shown in Fig. 4.

The cycles differ by a factor of kinetic energy conservation \( k_{SD} \) (cycle 1- \( k_{SD}=0.01 \), 2- \( k_{SD}=0.25 \), 3- \( k_{SD}=0.5 \), 4- \( k_{SD}=0.75 \)). Combustor parameters pressure \( p_c \), velocity \( u_c \) and maximum temperature \( T_c \) corresponding to each of these cycles are listed in Table 1. Value of \( T_c \) corresponds to completion of combustion process. Specific thrust of propulsion system \( F_r \) is given in the Table 1 as well.

![Fig. 4. The scramjet ideal Brayton cycles (case A): 1 - \( k_{SD}=0.01 \), 2 - \( k_{SD}=0.25 \), 3 - \( k_{SD}=0.5 \), 4 - \( k_{SD}=0.75 \) (initial and final points of the processes are numbered for the 1st cycle only).](image)

**Table 1. Characteristic parameters of scramjet ideal Brayton cycles (case A).**

<table>
<thead>
<tr>
<th>Factor ( k_{SD} )</th>
<th>0.01</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion pressure ( p_c ), atm</td>
<td>190</td>
<td>60</td>
<td>14</td>
<td>2.2</td>
</tr>
<tr>
<td>Velocity in combustor ( u_c ), m/s</td>
<td>243</td>
<td>1215</td>
<td>1710</td>
<td>2104</td>
</tr>
<tr>
<td>Maximum combustion temperature ( T_c ), K</td>
<td>4500</td>
<td>4070</td>
<td>3600</td>
<td>3160</td>
</tr>
<tr>
<td>Specific thrust ( F_r ), m/s</td>
<td>1083</td>
<td>1050</td>
<td>995</td>
<td>896</td>
</tr>
</tbody>
</table>

As it follows from Table 1 velocity increase in combustor leads to the significant reduction of \( p_c \) and \( T_c \), that is especially notable in the pressure. Nevertheless, it is noticed that in none of the cycles the constraints on velocity and static temperature in the combustor specified above are met simultaneously. Moreover, even for \( u_c = 2104 \)m/s > \( u_{lim} \) \( k_{SD}=0.75 \) \( T_c \) is significantly higher than \( T_{lim} \). We notice as well, that with velocity increase in the combustor a sharp deterioration of the cycle integral parameters due to rise of dissipation losses (entropy increment \( s_{3m-s_3} \)) in combustor with reduction of temperature.

The cycles of case B (conventional scramjet design with regard to shock-wave losses in diffusor) are given in Fig. 5.

Flow deceleration process in diffusor was determined with the same values of factor \( k_{SD} \). It will be recalled, that completion of this process was defined with application of deceleration curve, the technique of its construction is described above in the previous section. Numerical parameters of the cycles constructed are given in Table 2. We notice, that these cycles are considered as reference ones, because a comparison with them is used for evaluation of cases C and D.
Fig. 5. The reference scramjet cycles (case B): 1 - $k_{SD}=0.01$, 2 - $k_{SD}=0.25$, 3 - $k_{SD}=0.5$, 4 - $k_{SD}=0.75$ (initial and final points of the processes are numbered for the 1st cycle only).

**Table 2.** Characteristic parameters of reference scramjet cycles (case B).

<table>
<thead>
<tr>
<th>Factor $k_{SD}$</th>
<th>0.01</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion pressure $p_c$, atm</td>
<td>17.5</td>
<td>9</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Velocity in combustor $u_c$, m/s</td>
<td>243</td>
<td>1215</td>
<td>1710</td>
<td>2104</td>
</tr>
<tr>
<td>Maximum combustion temperature $T_{c max}$, K</td>
<td>4150</td>
<td>3800</td>
<td>3450</td>
<td>3075</td>
</tr>
<tr>
<td>Specific thrust $F_r$, m/s</td>
<td>896</td>
<td>858</td>
<td>801</td>
<td>741</td>
</tr>
</tbody>
</table>

Analysis of Figs. 4 and 5 shows, that the total entropy increment in the cycles A is much less than in reference cycles, though the entropy increment in combustor is nearly the same. Consequently, in the conventional scramjet scheme dissipation losses in supersonic diffuser and combustor are practically additive. It is seen from Table 2, that consideration of shock-wave losses in diffuser leads primarily to sharp reduction of pressure in combustor at slight temperature reduction. The propulsion system thrust decrease caused by account of shock-wave losses in diffuser is very high. Although in the reference cycles the combustor temperature is less than in the cycles A, its maximum value remains higher than maximum allowed temperature. That is to say that in the conventional scramjet design the problem of temperature reduction to allowable level cannot be solved, obviously, only by increase of flow velocity in the combustor.

Four cycles corresponded to AJAX design (case C) are shown in Fig. 6.

**Fig. 6.** The AJAX cycles (case C): 1 - $k_{SD}=0.5$, $k_g=0.5$, 2 - $k_{SD}=0.5$, $k_g=0.02$, 3 - $k_{SD}=0.75$, $k_g=0.67$, 4 - $k_{SD}=0.75$, $k_g=0.33$ (initial and final points of the processes are numbered for the 1st cycle only).

Values of factors $k_{SD}$, $k_g$ defining the cycle characteristics, and parameters $p_c$, $u_c$, $T_{c max}$ and $F_r$ are given in Table 3.

**Table 3.** Characteristic parameters of the AJAX cycles (case C).

<table>
<thead>
<tr>
<th>Factor $k_{SD}$</th>
<th>0.50</th>
<th>0.50</th>
<th>0.75</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor $k_g$</td>
<td>0.50</td>
<td>0.02</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>Combustion pressure $p_c$, atm</td>
<td>2.1</td>
<td>1.1</td>
<td>0.38</td>
<td>0.15</td>
</tr>
<tr>
<td>Velocity in combustor $u_c$, m/s</td>
<td>1215</td>
<td>243</td>
<td>1710</td>
<td>1215</td>
</tr>
<tr>
<td>Maximum combustion temperature $T_{c max}$, K</td>
<td>3400</td>
<td>3375</td>
<td>3000</td>
<td>2950</td>
</tr>
<tr>
<td>Specific thrust $F_r$, m/s</td>
<td>725</td>
<td>649</td>
<td>601</td>
<td>377</td>
</tr>
</tbody>
</table>

Analysis of Figs. 4 and 5 shows, that the total entropy increment in the cycles A is much less than in reference cycles, though the entropy increment in combustor is nearly the same. Consequently, in the conventional scramjet scheme dissipation losses in supersonic diffuser and combustor are practically additive. It is seen from Table 2, that consideration of shock-wave losses in diffuser leads primarily to sharp reduction of pressure in combustor at slight temperature reduction. The propulsion system thrust decrease caused by account of shock-wave losses in diffuser is very high. Although in the reference cycles the combustor temperature is less than in the cycles A, its maximum value remains higher than maximum allowed temperature. That is to say that in the conventional scramjet design the problem of temperature reduction to allowable level cannot be solved, obviously, only by increase of flow velocity in the combustor.

Four cycles corresponded to AJAX design (case C) are shown in Fig. 6.

One can see from comparison of Fig. 5 and Fig. 6 that dissipation losses in the cycles C are substantially greater than in the reference cycles. Besides that, with increase of bypassed energy determined by factor $k_g$ entropy increment increases and the specific thrust falls. This entropy increase is caused, on the one hand, by low temperature at which Joule heat release occurs in MHDG, and on the other hand, by notable reduction of average temperature of fuel burning in the combustor in comparison with the reference cycles. At the same time, as it follows from Table 3, the energy bypassing within the frames of AJAX design, in general, allows to reduce the combustor temperature down to allowable level with fulfillment of condition $u_c < u_{lim}$ (cycle 3), however in this case the cycle integral parameters are significantly impaired.

The cycles of case D for proposed in this paper RAM-MHD scheme are shown in Fig. 7.
Fig. 7. The RAM-MHD cycles (case D): 1 - \( k_{SD}=0.01 \), 2 - \( k_{SD}=0.125 \), 3 - \( k_{SD}=0.25 \), 4 – \( k_{SD}=0.5 \) (initial and final points of the processes are numbered for the 1st cycle only).

For their construction values of factor \( k_{SD} \) of 0.01, 0.125, 0.25 and 0.5 were used (at higher \( k_{SD} \) velocity in combustor exceeds \( u_{lim} \)). Calculated results for these four cycles are given in Table 4.

Table 4. Characteristic parameters of RAM-MHD cycles (case D)

<table>
<thead>
<tr>
<th>Factor ( k_{SD} )</th>
<th>0.01</th>
<th>0.125</th>
<th>0.25</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion pressure ( p_c ), atm</td>
<td>17</td>
<td>12</td>
<td>7</td>
<td>2.5</td>
</tr>
<tr>
<td>Velocity in combustor ( u_c ), m/s</td>
<td>243</td>
<td>862</td>
<td>1215</td>
<td>1710</td>
</tr>
<tr>
<td>Maximum combustion temperature ( T_{c max} ), K</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Specific thrust ( F_r ), m/s</td>
<td>743</td>
<td>738</td>
<td>731</td>
<td>720</td>
</tr>
</tbody>
</table>

It is recalled, in this scheme the processes in the second section of combustor as well as in MHDG (the third section of combustor) and MHDA proceed at the same temperature, i.e. follow one continuous isotherm \( T=T_{lim}=3000 \) K. As it is seen from Fig. 7 and Table 4 specific thrust achieves comparatively high values and has weak dependence on intensity of flow deceleration in the diffuser. Improvement of integral parameters in comparison with case C is connected both with increase of temperature in the inlet part of the combustor, i.e. fuel burning temperature in this section, and with temperature increase at which Joule heat release occurs in MHDG. In this case both temperature and pressure in MHDG channel are higher than those in the case of the AJAX scheme. It should be noticed, that effective operation of MHD devices at \( T=T_{lim} \) is much more realistic that in the case of the AJAX scheme.

Conclusion

1. At flight velocities corresponding to Mach number > 8 with application of fuel of heat caloric value > 800 kcal/kg in the conventional ramjet scheme the flow static temperature in a combustor may significantly exceed the maximum allowed values.

2. The MHD energy bypassing from the supersonic multishock diffuser to the nozzle in principle allows to reduce the combustor temperature down to allowable level, however in this case the propulsion system thrust falls significantly.

3. A principal capability exists to arrange the cycle with MHD bypassing of the flow energy from the combustor to the nozzle, while keeping the static temperature and the velocity at allowable levels in the engine flow train. The thermodynamic analysis shows that in this case the integral dissipative losses are minimized that results in higher values of specific thrust.

References


